Computer-Assisted Interactive Learning for Teaching Transmission Pricing Methodologies

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***Abstract*—This paper presents a computer-assisted method to teach and understand transmission pricing techniques. The education method is facilitated by specially designed user-friendly transmission pricing software (TPS). The proposed approach helps students fully understand transmission pricing through the fulfillment of the following educational objectives: 1) use of TPS to solve the transmission pricing problem of a small power system as well as a real-world power system; 2) complete understanding of the mathematics involved and development of software code to reproduce part of the results of TPS; 3) analysis of the results, identification and justification of the differences among three transmission tracing techniques and eight transmission cost allocation methods; and 4) extension of TPS methodologies. These methods have been proven effective in the education of students studying power system economics at the National Technical University of Athens (NTUA), Greece. A full-fledged, robust, comprehensive study of the educational improvements achieved through the use of TPS is provided.**

***Index Terms*—Computer simulation, electricity markets, interactive learning, Matlab, power engineering education, power system economics, sustainable energy systems, teaching.**

I. Introduction

IN deregulated electricity markets, cost allocation of transmission services is an important issue for all stakeholders [1]. The "beneficiary pays" principle is gaining more attention by the transmission network owners and operators throughout the world [2]. More efficient allocation of transmission cost to network users can promote the integration of renewable resources that are located far from load centers, thus contributing to power system sustainability [3]. Power flow based transmission pricing methodologies can measure network usage and calculate use of system charges for network users. These pricing methods can promote better utilization of network assets and provide the right signals for public acceptance of new transmission investments. Transmission pricing schemes have been developed and applied in various markets worldwide, e.g., Texas [4], Australia [5], Germany [6], and Greece [7]. An international comparison of electricity transmission pricing schemes can be found in [8].

In the fast changing electricity market environment, teaching power system economics and transmission pricing is a challenge. Integrating research results into a power engineering curriculum is also challenging [9]. The use of computer modeling and simulation in power engineering education is not a new concept [10], [11]. A number of educational papers have been published emphasizing the role of computer simulation for education in electricity markets and transmission pricing. Internet-based software has been developed and applied for teaching different day-ahead electricity market architectures [12]–[17], including the day-ahead electricity markets of Spain [13], Chile [16], European Union (EU) [17], and the USA wholesale power exchange market [14]. An evaluation of electricity market simulators can be found in [15]. Software has been also developed and applied for teaching transmission pricing [18], [19]. A computer-based transmission-pricing model helps students understand the evaluation of marginal wheeling costs for different types of power transactions [18]. A software tool has been developed to illustrate transmission spot pricing and to help gain insight on transmission congestion prices [19].

This paper presents a novel, computer-based approach to power engineering education in the field of transmission pricing. For the benefit of the students, a computer program, called transmission pricing software (TPS), has been developed to present the effects of various transmission fixed cost allocation methods. This tool itself is a significant contribution taking into account that, currently, there is no other software package that implements all the transmission pricing methodologies of TPS. The TPS is the basis for teaching transmission pricing in the context of the power system economics (PSE) course at the National Technical University of Athens (NTUA). The motivations for developing TPS is to enhance the power system economics course, bring the new world of electricity markets closer to the students, and provide a flexible simulation environment for ongoing research at NTUA. Taking into account that power engineering curricula in different countries include courses on electricity markets and power system economics [16], the teaching methods of transmission pricing methodologies proposed in this paper could be also useful for other curricula worldwide.

II. Power System Economics Course at NTUA

One of the compulsory courses at the sixth semester for the energy stream, of the five-year undergraduate curriculum for electrical and computer engineers at NTUA, is Power System Economics. It is a four-hour course per week, and its duration

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is 52 h (the academic semester has 13 weeks). During the last five years, on average, 250 students are enrolled annually in the course. The course material of the *Power System Economics* course includes the following lectures:

1) introduction, power generating plants, conventional and renewable energy sources, sustainable energy systems;
2) market overview of electric power systems;
3) basic concepts of economics applied to power systems, production cost of electrical energy, tariffs of electrical power and energy;
4) analysis and forecasting of load demand;
5) economic dispatch, unit commitment;
6) transmission networks and electricity markets, transmission cost allocation methods, congestion management, transmission pricing;
7) basic principles of reliability analysis, reliability indices, probability distributions for reliability evaluation, method of failure mode and effects analysis, method of minimal paths and cuts;
8) reliability analysis of power generation systems, basic probability methods, frequency and duration method.

III. Transmission Pricing Methodologies of TPS

A. Introduction

The cost of the basic transmission services corresponds primarily to the fixed transmission cost, also referred to as the embedded transmission facility cost. The cost of the transmission network can be interpreted as the cost of operation, maintenance and depreciation of the transmission system. Several methodologies have been proposed for the allocation of all or part of this network cost to transmission system users [2]. The embedded methods are more or less based on the actual network usage of a wheeling transaction while the marginal/incremental methods are based on the additional transmission cost a specific electricity transaction causes [20]. In the designed TPS, a centralized market is assumed and the locational marginal pricing method and various embedded cost allocation methods based on network usage are examined. Due to the nonlinear nature of power flow equations, it is impossible to physically decompose the network flows into components attributed to particular users. This fact necessitates the use of approximate models, sensitivity indices, or tracing algorithms to determine the contributions to the network flows from individual users or transactions [1].

B. Tracing Methodologies of TPS

In the context of the power system economics course of NTUA, three tracing algorithms are taught: 1) Generalized distribution factors or Rudnick method, 2) Bialek method, and 3) Minimum "power distance" method.

Generalized distributions factors are based on DC power flows and can be used as an efficient tool for evaluating transmission capacity use under various open access structures [21]. Generalized generation/load distribution factors (GGDFs/GLDFs) depend on line parameters, system conditions and not on the reference bus location. The implied assumption for this tracing methodology is that each load is assigned in a pro rata basis to the committed generators.

In *Bialek tracing algorithm*, the topological approach is used and the topological distribution factors are calculated in order to determine the contribution of individual generators or loads to every line flow [22]. The method allows tracing the output of every generator or input to every load, assuming that nodal inflows are shared proportionally between the outflows. The method uses either the upstream-looking algorithm or the downstream-looking algorithm whether the transmission usage charges are allocated to generators or loads, respectively. As the shares are always greater than zero, no counter-flow problems are encountered and all the charges to the network users are positive. The simplicity is the main advantage of the method.

In the *minimum power distance method*, it is assumed that electricity flows through paths that minimize the total MW-km covered in the power system. Based on the linearity of the DC model of the network and the introduction of the *power distance* term, a linear minimization problem provides an allocation of generation to loads (minimum power distance transactions) [23]. This assignment allows decomposing every real flow of the network in "partial flows" according to each pair of generation and load, as if it was a predefined bilateral transaction.

C. Transmission Cost Allocation Methods of TPS

In the transmission pricing course, eight transmission cost allocation embedded methods are presented: 1) postage stamp; 2) MW-Mile (original); 3) unused absolute; 4) unused reverse; 5) unused zero counter-flow; 6) used absolute; 7) used reverse; and 8) used zero counter-flow.

In *Postage stamp* method, an entity pays a rate equal to a fixed charge per unit of energy (capacity) transmitted. Charges are calculated taking into account the magnitude of the user's transacted power in a certain snapshot of the system (e.g., system peak load) and do not reflect the actual use of the system.

The original *MW-Mile* method (*MWM original*) allocates transmission fixed cost based on the "extend of use" of the network from each user. The method ensures full recovery of network costs and reflects the relative usage of the whole transmission system MW-Miles.

Instead of charging network users for the relevant usage of the whole network facilities, total charges for each network facility can be based either on the unused (total) transmission capacity or on the used capacity of the facilities [1]. When based on the *unused* transmission capacity, full recovery of the transmission fixed cost is guaranteed, while for the *used* transmission capacity methods supplementary charges usually occur. The charges for this reliability margin cost of the facility can be calculated through other embedded methods (e.g., postage stamp, MWM).

There are three different approaches in relation with the way users that cause *counter-flows* in the network are charged [24]: 1) absolute; 2) reverse; and 3) zero counter-flow method.

In the *absolute* method, charges are calculated based on the magnitude of users contributions, ignoring the direction of the power flows on the circuit (counter-flows are charged).

The *reverse* approach takes into account power contributions that are in the opposite direction of the net flows and charges for each line are based on the net flows (counter-flows are credited).

In the *zero counter-flow method* (ZCF), contributions opposite to the net flows are not counted. Users responsible for these counter-flows do not pay any charge (as happens in the absolute methods) and do not receive any credit (as happens in reverse methods).

IV. Transmission Pricing Educational Tool

A. Motivation

One reason for developing the TPS educational tool is to enhance the power system economics course and to provide a flexible simulation environment for ongoing research at NTUA [25], [26]. The TPS brings the concepts of electricity markets closer to the students of NTUA.

Detailed and efficient industry software is available for the analysis, operation and planning of electric power systems. However, professional software is not well suited for classroom purposes, as the embedded models may lack intuitiveness, their modification may be difficult, and it takes time to master complex software. Also, students may not have an easy access to these tools. Matlab [11] is already widely used in engineering courses and well known by students. Moreover, currently, there is no single professional software package that includes all the transmission pricing methodologies of Section III. Therefore Matlab has been used to develop the TPS, which implements all the methodologies of Section III.

B. Main Features

When developing the TPS educational tool, attention has been paid to the following aspects:

1) *modularity*: the necessary functions are fully parametric and, through their input and output parameters, can be simply called to perform multiple sensitivity analysis studies;
2) *maintenance and extension*: the "Developers Guide" facilitates the maintenance and extension of TPS in an easy way; the input and output files have common format irrespective of the tracing and pricing method;
3) *simplicity of use*: the graphical user interface (Section IV-C) makes the use of TPS easy for students;
4) *transparency*: the developed functions match the theoretical transmission pricing models of Section III; programming tricks have been practically avoided, even at the cost of computational efficiency.

C. Graphical User Interface

The GUIDE toolbox of Matlab has been used for the implementation of the graphical user interface (GUI) of TPS. The GUI helps students arrive at the final solution by visualizing each step of the solution process. Moreover, GUIs are increasingly used to provide users of computer simulations a friendly and visual approach. Using TPS, students can see key intermediate results, e.g., the contribution of network users to transmission line flows, before arriving in the final solution, i.e., the cost allocation among network users.

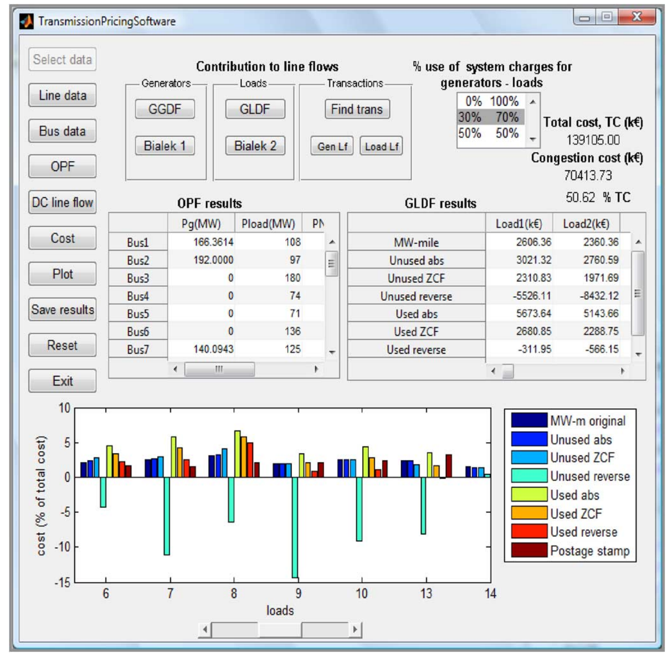

Fig. 1. Indicative results of TPS GUI.

D. Brief Presentation

In TPS, the student can insert all the necessary data in the form of a Microsoft Excel or a text file. Next, the students can select the percentage of total fixed transmission cost that is charged to generators and loads from the list box at the top right of the GUI (Fig. 1) among the three available options: (a) 0%–100%, (b) 30%–70%, and (c) 50%-50%. For the calculation of transmission power flows, students have two alternatives. Power flows may come either from the results of an optimal power flow (OPF) calculation or from a DC power flow calculation using the fixed generation input data. In the first case, the final dispatch of the generators is not known *a priori* and depends on the generators costs or bids. From the results of the OPF, locational marginal prices (LMPs) are calculated for each bus of the network. The total congestion revenue from this marginal pricing of transmission is computed for all lines and is also displayed as a percentage of the total cost (TC), as Fig. 1 shows.

For computing the contribution of generators to line flows, students can select: 1) the GGDF method; 2) Bialek upstream method; and 3) the minimum power distance method.

For computing the approximate contribution of loads to line flows, students can select: 1) the GLDF method; 2) Bialek downstream method; and 3) the minimum power distance method.

Next, the transmission use of system charges for the loads and the generators are calculated using the eight different transmission pricing methods of Section III-C.

The final results may be plotted in the GUI and the detailed results can be saved in a Microsoft Excel file. This option is very useful, because the analysis of results helps the student understand better the various transmission tracing and pricing methodologies, as will be shown in Section VII.

V. Pedagogical Issues in Computer-Assisted Interactive Learning

According to Bloom's taxonomy [27], the learning and understanding of human can be classified into six hierarchical levels: 1) knowledge; 2) comprehension; 3) application; 4) analysis; 5) synthesis; and 6) evaluation. The level of understanding and the ability to apply given principles increase by moving upwards in the pyramid, i.e., from level 1 (knowledge) to level 6 (evaluation). Advanced undergraduate engineers, like the students following the PSE course at NTUA, and practicing engineers usually operate at level 3 [28], [29]. Graduate engineers and research engineers usually operate at levels higher than 3 [29].

Since the 1960s, computer-assisted interactive learning has been proved a valuable means for the enhancement of education [30], [31]. The core educational objective of the proposed computer-assisted interactive learning is to enhance the learning of PSE course in order the students to be able to operate at the higher Bloom levels (analysis, synthesis, and evaluation) when faced with complex transmission pricing problems. This objective, detailed in Section VII-A, was achieved thanks to the well-structured methodology of Section VII. The higher Bloom level operation was assessed by written exams, which show that the grades of the students have been increased after the introduction of the proposed method.

VI. Teaching Method

The objective of the transmission pricing unit of the Power System Economics course at NTUA is to present several transmission pricing methods to the students and allow them to practice with various generation and demand scenarios in order to understand the advantages and disadvantages of each pricing method.

At the beginning of the semester, a user guide of TPS is distributed to the students together with transmission pricing educational examples with detailed presentation of the calculations involved. The teaching is implemented as follows. The instructor presents in the class the transmission pricing theory together with some simple arithmetic examples. Then, the use of TPS is presented, using attractive slide presentations and animation graphics. Groups of 48 students are formed and each student uses one of the lab computers to solve the transmission pricing problem on Garver's six bus power system [32], using TPS. The instructor, aided by four advanced postgraduate students, facilitates the students to solve this problem. In brief, the computer-assisted interactive teaching strategy is as follows: 1) study a problem; 2) study a solution; 3) solve by hand; 4) verify by computer using TPS; and 5) repeat for different input parameters. At the end of the transmission pricing course, a small presentation of the Greek interconnected transmission system is also made, along with the results of the TPS for certain snapshots of the Greek power system.

Thanks to the interactive learning environment of TPS, while solving a transmission pricing problem, the students can see the solution of the problem, on a step-by-step basis: 1) parametric data entry; 2) calculation of transmission line flows; 3) calculation of the contribution of network users to line flows; 4) computation of charges for network users; and 5) analysis of results and understanding the characteristics of each transmission pricing method. This interactive learning environment has been proved very effective in the classroom, since most engineering students are active learners.

TABLE I
LINE DATA FOR GARVER 6-BUS TEST SYSTEM

From Bus	To Bus	Reactance (pu)	Length (km)	Capacity (MW)	Investment (k€)
1	2	0.40	40	100	40
1	4	0.60	60	80	60
1	5	0.20	20	100	20
2	3	0.20	20	100	20
2	4	0.40	40	100	40
3	5	0.10	20	200	40
2	6	0.15	30	200	60
4	6	0.15	30	200	60
Total Annuitized Cost of Investment (k€)					340

TABLE II
BUS DATA FOR GARVER 6-BUS TEST SYSTEM

Bus	Generator Offer (€/MWh)	Min Generation (MW)	Max Generation (MW)	Load (MW)
1	10	0	150	80
2	–	–	–	240
3	20	0	360	40
4	–	–	–	160
5	–	–	–	240
6	30	0	600	–

VII. Results and Discussion

A. Educational Objectives

The core educational objective of making students able to operate at the higher Bloom levels is achieved through the fulfillment of the following individual educational objectives:

1) use of TPS to solve the transmission pricing problem of a small power system (Garver 6-bus) as well as a real-world power system;
2) complete understanding of the mathematics involved and development of software code to reproduce part of the results of TPS;
3) analysis of the results and understanding of the concepts of LMPs, congestion rent, and congestion cost;
4) analysis of the results, identification and justification of the differences among the three transmission tracing techniques and the eight transmission cost allocation methods;
5) extension of TPS methodologies. This objective is dedicated to the students who are interested to make their dissertation in transmission pricing.

B. Garver 6-Bus Test System

1) Brief Description of the Laboratory Exercise: The students are given the line data and the bus data of Garver 6-bus test system, shown in Tables I and II, respectively. Bus 1 is the reference bus. The per unit (pu) values in Table I are expressed on a 100-MVA power base.

As a first step, they are requested to compute the power flows by an OPF calculation using TPS as well as their own OPF software code using the linprog command of Matlab. Next, using

TABLE III
UNCONSTRAINED CASE RESULTS FOR GARVER 6-BUS TEST SYSTEM

BUS	LMP (€/MWH)	GENERATION (MW)	LOAD (MW)	CREDIT (€/H)	CHARGE (€/H)	DISPATCH COST (€/H)
1	30.00	150	80	4 500	2 400	1 500
2	30.00	–	240	–	7 200	–
3	30.00	360	40	10 800	1 200	7 200
4	30.00	–	160	–	4 800	–
5	30.00	–	240	–	7 200	–
6	30.00	250	–	7 500	–	7 500
	TOTAL	**760**	**760**	**22 800**	**22 800**	**16 200**

TABLE IV
CONSTRAINED CASE RESULTS FOR GARVER 6-BUS TEST SYSTEM

BUS	LMP (€/MWH)	GENERATION (MW)	LOAD (MW)	CREDIT (€/H)	CHARGE (€/H)	DISPATCH COST (€/H)
1	40.21	150	80	6 032	3 217	1 500
2	28.72	–	240	–	6 893	–
3	20.00	333.19	40	6 664	800	6 664
4	31.28	–	160	–	5 005	–
5	48.93	–	240	–	11 743	–
6	30.00	276.81	–	8 304	–	8 304
	TOTAL	**760**	**760**	**21 000**	**27 658**	**16 468**

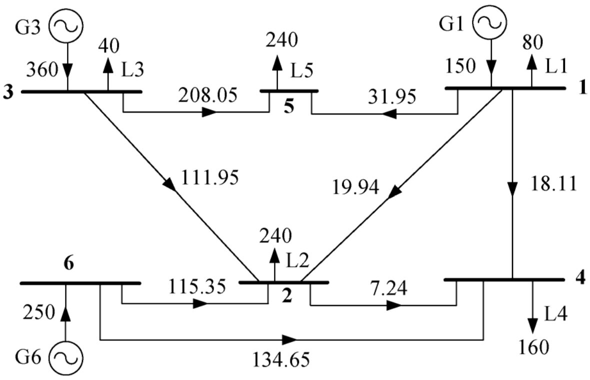

Fig. 2. Unconstrained case results (power flows are in MW).

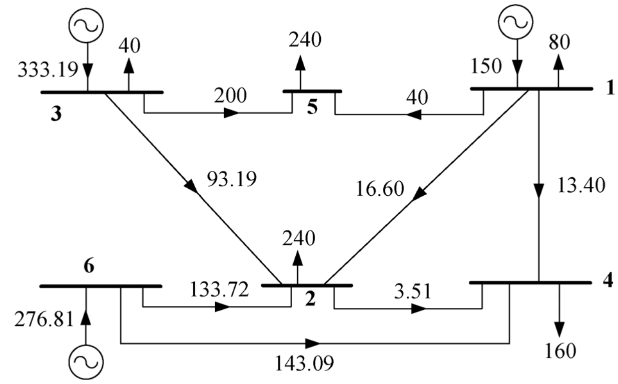

Fig. 3. Constrained case results (power flows are in MW).

the power flows of the first step, they calculate the LMPs, congestion rent and congestion cost of the specific snapshot, and then they allocate the embedded annual transmission service cost by charging equally the producers and consumers considering only the provided system snapshot. Finally, the students have to analyze the results and derive conclusions.

2) LMPs, Congestion Rent and Congestion Cost: The unconstrained case (ignoring the line capacity limits) OPF results, obtained by TPS, are shown in Table III and Fig. 2. Thanks to appropriate training, the students easily develop software code in Matlab to solve the same OPF problem and obtain the same power flows, as the ones shown in Fig. 2. The presentation of results in the form of Fig. 2 is very useful for the students, since they can easily confirm the nodal power balance equations. Analyzing the results of Table III, they realize that the LMPs at all nodes are the same, because the line capacity limits are ignored. Since it is a lossless power system, the students figure out that the total generation is equal to the total load (760 MW), and because all nodes have the same LMPs (€30/MWh), the total credit to the generators is equal to the total charge of loads (€22 800/h). The students understand that the total dispatch cost (€16 200/h) is obtained by calculating the generator bids (2nd column of Table II) at the optimal generation dispatch (3rd column of Table III).

The OPF results for the constrained case (considering line capacity limits) are shown in Table IV and Fig. 3. The educational value of Fig. 3 is that the students can find that the line 3–5 operates at its limit (200 MW), while all other lines operate below their capacity limit. They also realize that LMPs are different at every bus. Using the results of Tables IV, they can compute the congestion rent (also called merchandising surplus), which is the difference between the payments by load (€27 658/h) minus the payments to generation (€21 000/h), so the congestion rent is €6658/h. The students are informed that the congestion rent represents revenue that maybe partially distributed back to market participants through financial transmission rights.

Using the results of Tables III and IV, the students can compute the congestion cost. More specifically, the congestion cost is the difference between the cost of dispatch for the constrained case (€16 468/h) minus cost of dispatch for the unconstrained case (€16 200/h), so the congestion cost is €268/h. The students realize that this congestion cost represents the increased cost of fuel needed and the loss in social welfare due to the finite capacity of transmission system.

3) Transmission Pricing: Using TPS, the students compute the contribution of producers (G1, G3, and G6 defined in Fig. 2) to line flows, corresponding to the constrained case of Fig. 3, using the three different tracing methods, as shown in Table V. Similarly, TPS computes the contribution of consumers (L1, L2, L3, L4, and L5 defined in Fig. 2) to line flows (the results are not shown due to space limitations). One educational value of Table V is that the students very easily identify the generators that cause counter-flows. For example, using the GGDF tracing method, the power flow of 16.60 MW on line 1–2 is due to a flow of 41.24 MW due to G1, a flow of 5.38 MW due to G3, and a counter-flow of 30.02 MW due to generator G6.

It can be seen from Table I that the total annuitized cost of investments in transmission lines is 340 k€. Since the students were requested to charge equally the producers and consumers, it means that producers will pay 170 k€ and consumers will also pay 170 k€. Using TPS, the students compute the charges for producers and consumers using the eight different pricing methods and the results are shown in Table VI. Analyzing the results of Tables V and VI, the students have the opportunity

TABLE V
CONTRIBUTION OF PRODUCERS G1, G3, AND G6 TO LINE POWER FLOWS FOR GARVER 6-BUS TEST SYSTEM

LINE		LINE FLOW (MW)	TRANSMISSION TRACING METHOD								
			GGDF			BIALEK UPSTREAM			MINIMUM TRANSACTIONS		
FROM	TO		G1 (MW)	G3 (MW)	G6 (MW)	G1 (MW)	G3 (MW)	G6 (MW)	G1 (MW)	G3 (MW)	G6 (MW)
1	2	16.5957	41.2393	5.3786	-30.0221	16.5957	0.0000	0.0000	12.0767	6.5889	-2.0699
1	4	13.4043	28.4009	18.3768	-33.3734	13.4043	0.0000	0.0000	6.2620	3.4165	3.7258
1	5	40.0000	64.5704	-58.8282	34.2578	40.0000	0.0000	0.0000	51.6613	-10.0054	-1.6559
3	2	93.1915	9.3072	151.6086	-67.7243	0.0000	93.1915	0.0000	-18.3387	113.1861	-1.6559
2	4	3.5106	1.3620	22.1866	-20.0380	0.2393	1.3435	1.9279	-2.6837	-1.4642	7.6586
3	5	200.0000	-17.2020	164.0465	53.1554	0.0000	200.0000	0.0000	18.3387	180.0054	1.6559
6	2	133.7234	-1.8160	-29.5822	165.1216	0.0000	0.0000	133.7234	3.5783	1.9523	128.1928
6	4	143.0851	1.8160	29.5822	111.6869	0.0000	0.0000	143.0851	-3.5783	-1.9523	148.6157

to identify and justify the differences among the three transmission tracing techniques and the eight transmission cost allocation methods. This opportunity significantly enhances their learning capabilities. More specifically, for the specific system snapshot, they derive the following conclusions:

1) Five out of eight transmission pricing methods fully recover the total cost for producers (170 k€) and the total cost for consumers (170 k€). These methods are: a) original MW-mile; b) unused absolute; c) unused ZCF; d) unused reverse; and e) postage stamp.
2) The used ZCF and the used reverse methods under-recover the total cost for producers and consumers. The students realize that this is due to the fact that the used methods charge the transmission investments based on the used capacity of the lines, which is typically below the capacity limit for most of the lines. More specifically, in the considered constrained case study, only one line operates at its capacity limit. The students also understand that the application of the used ZCF and the used reverse methods has to be combined with an additional pricing method (e.g., the postage stamp) in order to distribute among the users a supplementary charge to fully recover the transmission investment cost.
3) It is possible that the used absolute and the used ZCF methods over recover a line's fixed cost due to the high values of counter-flows that are all charged. An adjustment in each line's calculated charges is needed in order total charges for a line do not exceed line's annual fixed cost.
4) The unused reverse method computes some spikes (very high charges or credits) for some users, which is not easy to be accepted by all the network users.

After discussion with their instructors, who apply a question and answer interactive approach on the basis of TPS results, the students are facilitated to derive the following advanced conclusions:

5) Maybe the most fair is the unused ZCF method because: a) it fully recovers the total transmission investment cost, thus providing a satisfactory income for the transmission owner; and b) it gives economic incentives for the users that cause counter-flows.
6) Bialek tracing method creates only positive contributions to line flows. That is why the same charges are computed by the three different methods of charging counter-flows, i.e., a) unused absolute, unused ZCF, and unused reverse; and b) used absolute, used ZCF, and used reverse.
7) Bialek and minimum transactions methods can compute zero charges for some users. On the other hand, GGDF/GLDF methods charge all users, because all users utilize the transmission system.

C. *Greek Interconnected Power System*

The instructor presents briefly the Greek interconnected transmission system, along with the results of the TPS for certain snapshots. Such a snapshot, corresponding to a total loading of 10 000 MW, is shown in Table VII along with the separation of the power system into seven areas. The transmission system total costs are estimated to be €191M/yr. Fig. 4 shows the charge for the seven areas of the Greek power system using GLDFs. Moreover, Fig. 4 shows the total charge for all areas, which is an indicator of charges differentiation per cost allocation method. After discussion with the students, the results of Fig. 4 are analyzed in combination with the data of Table VII and the following main conclusions are drawn:

1) The original MW-mile, the unused absolute, the unused ZCF, and the postage stamp method fully recover the total transmission fixed cost, while there is a small recovery of the total cost by the used methods.
2) For all the different pricing methods, the biggest charge is allocated to area 5 (Attica) that serves the highest load.
3) The smallest charge is generally allocated to area 2 (West Macedonia) that serves the minimum load while producing the maximum power.

D. *Extensions*

The instructor presents ideas for extension of TPS methodologies. The objective is to attract students interested to make their dissertation in transmission pricing. The main results of two such dissertations can be found in [25] and [26].

E. *Assignments*

After completion of the computer laboratory exercise, the students are assigned a small project in order to investigate the eight transmission pricing and the three tracing methodologies on the IEEE 24-bus reliability test system and deliver a report with the results and conclusions of their simulation. Teams of three students are formed. Each team is given: 1) different generation and loading scenario; and 2) different bilateral transactions between different generators and loads of the test system.

TABLE VI
PRODUCERS AND CONSUMERS CHARGES (k€) FOR GARVER 6-BUS TEST SYSTEM

TRACING METHOD	USER	CHARGES (K€) PER TRANSMISSION COST ALLOCATION METHOD							
		MWM	UNUSED ABSOLUTE	UNUSED ZCF	UNUSED REVERSE	USED ABSOLUTE	USED ZCF	USED REVERSE	POSTAGE STAMP
GGDF	G1	20.9056	28.6455	44.5564	136.4164	28.8234	26.8308	24.8382	33.5526
	G3	59.6512	53.5398	63.6658	191.5393	58.7273	48.4072	38.0870	74.5297
	G6	89.4432	87.8147	61.7778	-157.9557	79.5621	50.2626	20.9631	61.9177
	TOTAL	170.0000	170.0000	170.0000	170.0000	167.1128	125.5005	83.8883	170.0000
GLDF	L1	18.9316	19.6639	8.9995	-54.8607	20.1725	7.8779	-4.4167	17.8947
	L2	39.5449	40.1368	46.7479	-28.9965	42.4646	36.8629	31.2612	53.6842
	L3	6.7363	5.8458	3.8743	-14.0471	6.4525	3.1476	-0.1572	8.9474
	L4	46.1021	52.9041	69.5209	342.9535	49.2850	43.7657	38.2465	35.7895
	L5	58.6851	51.4495	40.8574	-75.0492	55.2695	37.1120	18.9545	53.6842
	TOTAL	170.0000	170.0000	170.0000	170.0000	173.6441	128.7662	83.8883	170.0000
BIALEK UPSTREAM	G1	13.4069	61.3630	61.3630	61.3630	12.3936	12.3936	12.3936	33.5526
	G3	58.3773	37.6540	37.6540	37.6540	29.5879	29.5879	29.5879	74.5297
	G6	98.2158	70.9830	70.9830	70.9830	41.9068	41.9068	41.9068	61.9177
	TOTAL	170.0000	170.0000	170.0000	170.0000	83.8883	83.8883	83.8883	170.0000
BIALEK DOWNSTREAM	L1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	17.8947
	L2	61.2109	59.1350	59.1350	59.1350	32.2254	32.2254	32.2254	53.6842
	L3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	8.9474
	L4	56.9901	80.8650	80.8650	80.8650	27.6629	27.6629	27.6629	35.7895
	L5	51.7990	30.0000	30.0000	30.0000	24.0000	24.0000	24.0000	53.6842
	TOTAL	170.0000	170.0000	170.0000	170.0000	83.8883	83.8883	83.8883	170.0000
MINIMUM TRANSACTIONS	G1	15.1430	17.5744	21.4082	26.1137	15.2077	12.3003	9.3930	33.5526
	G3	63.0994	59.9196	55.9022	34.9188	53.7301	42.1774	30.6247	74.5297
	G6	91.7576	92.5060	92.6896	108.9675	66.1289	54.9998	43.8706	61.9177
	TOTAL	170.0000	170.0000	170.0000	170.0000	135.0667	109.4775	83.8883	170.0000
	L1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	17.8947
	L2	65.3700	69.9139	62.3642	-78.5172	54.6689	41.1836	27.6982	53.6842
	L3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	8.9474
	L4	53.0375	52.6265	64.1326	215.8630	38.2236	35.4633	32.7029	35.7895
	L5	51.5925	47.4595	43.5032	32.6542	42.1741	32.8307	23.4872	53.6842
	TOTAL	170.0000	170.0000	170.0000	170.0000	135.0667	109.4775	83.8883	170.0000

TABLE VII
AREAS DATA FOR 10 000 MW LOADING OF THE GREEK POWER SYSTEM

AREA	DESCRIPTION	GENERATION (MW)	LOAD (MW)
AREA 1	EAST MACEDONIA AND THRACE	1 708	1 976
AREA 2	WEST MACEDONIA	4 129	920
AREA 3	THESSALY	45	963
AREA 4	EAST CENTRAL GREECE & EUVOIA	614	1 134
AREA 5	ATTICA	1 769	3 451
AREA 6	PELOPONNESE	736	932
AREA 7	WEST CENTRAL GREECE, EPIRUS, AND IONIAN ISLANDS	999	624
	TOTAL	10 000	10 000

VIII. STUDENT FEEDBACK

The TPS-assisted interactive learning environment has been used during the last three years at the National Technical University of Athens to help teach the undergraduate course of power system economics. The students easily learn how to use this software thanks to its well-designed user interface and due to their prior familiarization with Matlab.

This computer-assisted interactive learning approach was assessed both formally with student evaluations using the standard questionnaire of NTUA as well as informally through open discussions with students. Students rated the education material and the software positively and course evaluations were higher after these interactive learning tools were introduced. In fact, this software helps students clarify the concept of transmission pricing in pool based electricity markets and comprehend the attributes of the examined distribution factors.

The formal evaluation of the courses through a standard questionnaire is a common practice in the school of electrical and computer engineering of NTUA. This questionnaire is composed of ten questions: the first six questions are related with the course and the last four questions are related with the teachers and the educational materials. Table VIII shows the average score for each question from the feedback of 185 students during the academic year 2011–2012. It can be seen that the usefulness of the practical computer examples in understanding the course is rated very high. This conclusion is further verified by Fig. 5, which presents the average evaluation of the usefulness of the practical computer examples in understanding the course for the following cases: 1) four other courses with the same instructors as PSE; 2) PSE course before the introduction of TPS; and 3) PSE after the introduction of the proposed computer-assisted learning.

After the introduction of the computer-assisted interactive learning approach, the number of students who select the power

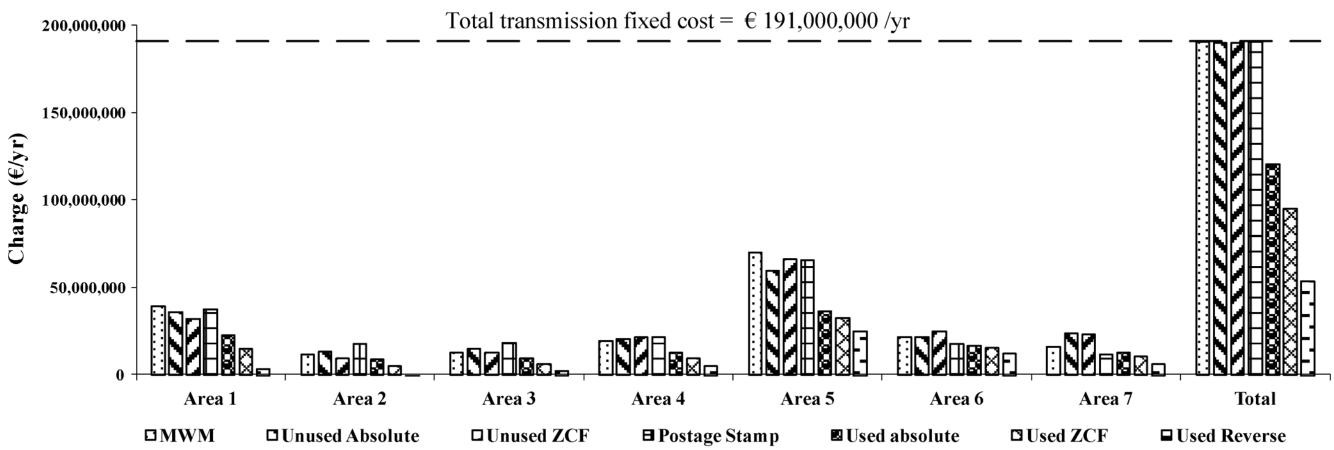

Fig. 4. Charge (€/yr) for the seven areas of the Greek interconnected power system using GLDFs.

TABLE VIII
QUESTIONNAIRE AND AVERAGE EVALUATION

QUESTION	SCORE
Is the prerequisite knowledge covered by other already taught courses? (1=insufficiently, 5=average, 10=absolutely)	7.34
Is the content of the course taught in other courses? (1=no, 5=at 50%, 10=at 100% i.e. nothing is new in this course)	2.29
Number of teaching hours for covering the course content (1=insufficient, 5=reasonable, 10=excessive)	5.26
Quantity of the necessary homework (1=insufficiently, 5=reasonable, 10=excessive)	5.15
Organization of the course (1=most negative, 10=most positive)	8.57
Interest of the course based on its content (1=most negative, 10=most positive)	8.17
Communicativeness of the teachers (1=most negative, 10=most positive)	8.32
Usefulness of the practical computer examples in understanding the course (1=most negative, 10=most positive)	8.94
Reliability of the teachers in their educational obligations (1=most negative, 10=most positive)	8.45
Adequacy and usefulness of the educational materials (1=most negative, 10=most positive)	7.85

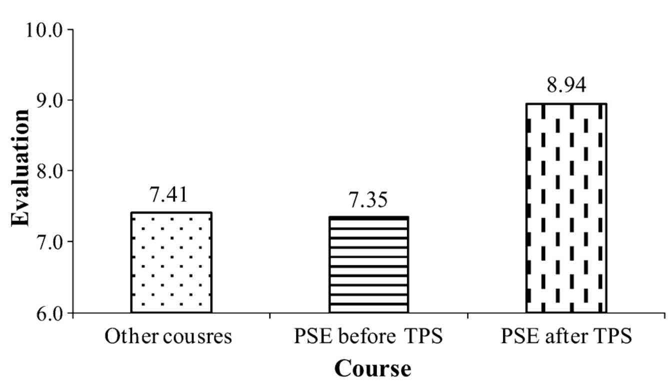

Fig. 5. PSE and other courses average evaluation of the usefulness of the practical computer examples in understanding the course.

system economics course for their Diploma dissertation was increased. These students focus on algorithm development using Matlab environment and also take care for the implementation of a user-friendly graphical user interface. All these findings provide incentives for implementing similar computer-aided education methodologies to other courses as well.

IX. CONCLUSION

A computer-assisted interactive learning environment has been developed and successfully used in the teaching of power system economics course of the sixth semester of the five-year undergraduate curriculum of electrical and computer engineering at NTUA, Greece. Students learn very easily how to use the transmission pricing software thanks to its well-designed GUI. The tool helps them clarify the differences of the eight transmission pricing and the three tracing methodologies. Students rate the software and the education material very positively and the overall course is evaluated higher after this tool was introduced. The number of students who select the power system economics course for their Diploma dissertation has been increased. The relevant Diploma projects place special emphasis on algorithms development using Matlab and its GUI development toolbox.

REFERENCES

[1] M. Shahidehpour, H. Yamin, and Z. Li, *Market Operations in Electric Power Systems: Forecasting, Scheduling and Risk Management*. New York, NY, USA: Wiley, 2002.
[2] J. Pan, Y. Teklu, and S. Rahman, "Review of usage-based transmission cost allocation methods under open access," *IEEE Trans. Power Syst.*, vol. 15, no. 4, pp. 1218–1224, Nov. 2000.
[3] G. A. Orfanos, P. S. Georgilakis, and N. D. Hatziargyriou, "Transmission expansion planning of systems with increasing wind power integration," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1355–1362, May 2013.
[4] M. L. Baughman, "Pricing of open-access transmission services in Texas," *Util. Policy*, vol. 6, no. 3, pp. 195–201, Sep. 1997.
[5] N. H. Radzi, R. C. Bansal, Z. Y. Dong, M. Y. Hassan, and K. P. Wong, "An efficient distribution factors enhanced transmission pricing method for Australian NEM transmission charging scheme," *Renew. Energy*, vol. 53, pp. 319–328, May 2013.
[6] M. Niederprüm and M. Pickhardt, "Electricity transmission pricing: The German case," *Atlantic Econ. J.*, vol. 30, no. 2, pp. 136–147, Jun. 2002.
[7] A. Bakirtzis, P. Biskas, A. Maissis, A. Coronides, J. Kabouris, and M. Efstathiou, "Comparison of two methods for long-run marginal cost-based transmission use-of-system pricing," *IEE Proc. Gener. Transm. Distrib.*, vol. 148, no. 4, pp. 477–481, Jul. 2001.
[8] R. Green, "Electricity transmission pricing: An international comparison," *Util. Policy*, vol. 6, no. 3, pp. 177–184, Sep. 1997.

[9] M. L. Crow, C. Singh, K. J. Olejniczak, K. Tomsovic, R. Christie, A. Pahwa, and K. Y. Lee, "Integrating research results into a power engineering curriculum," *IEEE Trans. Power Syst.*, vol. 14, no. 2, pp. 404–411, May 1999.

[10] M. Kezunovic, A. Abur, G. Huang, A. Bose, and K. Tomsovic, "The role of digital modeling and simulation in power engineering education," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 64–72, Feb. 2004.

[11] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "MATPOWER: Steady-state operations, planning, analysis tools for power systems research and education," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 12–19, Feb. 2011.

[12] R. D. Zimmerman, R. J. Thomas, D. Gan, and C. Murillo-Sánchez, "A web-based platform for experimental investigation of electric power auctions," *Decision Support Syst.*, vol. 24, no. 3–4, pp. 193–205, Jan. 1999.

[13] J. Contreras, A. J. Conejo, S. de la Torre, and M. G. Muñoz, "Power engineering lab: Electricity market simulator," *IEEE Trans. Power Syst.*, vol. 17, no. 2, pp. 223–228, May 2002.

[14] T. Sueyoshi and G. R. Tadiparthi, "A wholesale power trading simulator with learning capabilities," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1330–1340, Aug. 2005.

[15] M. B. A. Kopaee, M. Manbachi, H. Khezeli, M. S. Ghazizadeh, and A. Rahimi-Kian, "NetPMS: An internet-based power market simulator for educational purposes," *IET Gener. Transm. Distrib.*, vol. 6, no. 5, pp. 472–481, May 2012.

[16] J. Y. Guevara-Cedeño, R. Palma-Behnke, and R. Uribe, "Experimental economics for teaching the functioning of electricity markets," *IEEE Trans. Educ.*, vol. 55, no. 4, pp. 466–473, Nov. 2012.

[17] Q. C. Trinh, M. Saguan, and L. Meeus, "Experience with electricity market test suite: Students versus computational agents," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 112–120, Feb. 2013.

[18] C. W. Yu, "Developing a computer-based transmission-pricing model for power market operation teaching," *Int. J. Elect. Eng. Educ.*, vol. 41, no. 3, pp. 202–215, Jul. 2004.

[19] T. W. Cedra, "Transmission spot pricing illustrated: Using an interactive graphical tool to gain insight on network congestion prices," in *Proc. 28th Annual Frontiers of Power Conf.*, Stillwater, OK, USA, Oct. 1995.

[20] D. Shirmohammadi, X. V. Filho, B. Gorenstin, and M. V. P. Pereira, "Some fundamental technical concepts about cost based transmission pricing," *IEEE Trans. Power Syst.*, vol. 11, no. 2, pp. 1002–1008, May 1996.

[21] H. Rudnick, M. Soto, and R. Palma, "Use of system approaches for transmission open access pricing," *Int. J. Elect. Power Energy Syst.*, vol. 21, no. 2, pp. 125–135, Feb. 1999.

[22] J. Bialek, "Tracing the flow of electricity," *Proc. IEE Gener. Transm. Distrib.*, vol. 143, no. 4, pp. 313–320, Jul. 1996.

[23] P. Barcia and R. Pestana, "Tracing the flows of electricity," *Int. J. Elect. Power Energy Syst.*, vol. 32, no. 4, pp. 329–332, May 2010.

[24] Z. Jing, X. Duan, F. Wen, Y. Ni, and F. F. Wu, "Review of transmission fixed cost allocation methods," in *Proc. IEEE Power Eng. Soc. General Meeting*, Toronto, ON, Canada, 2003.

[25] G. Orfanos, G. Tzasiou, P. Georgilakis, and N. Hatziargyriou, "Evaluation of transmission pricing methodologies for pool based electricity markets," in *Proc. IEEE PowerTech Conf.*, Trondheim, Norway, 2011.

[26] G. A. Orfanos, P. S. Georgilakis, and N. D. Hatziargyriou, "A more fair power flow based transmission cost allocation scheme considering maximum line loading for N-1 security," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3344–3352, Aug. 2013.

[27] D. R. Krathwohl, B. S. Bloom, and B. Masia*, Taxonomy of Educational Objectives: The Classification of Educational Goals. Handbook II: The Affective Domain*. New York, NY, USA: David McKay, 1964.

[28] H. Ni, G. T. Heydt, D. J. Tylavsky, and K. E. Holbert, "Power engineering education and the internet: Motivation and instructional tools," *IEEE Trans. Power Syst.*, vol. 17, no. 1, pp. 7–12, Feb. 2002.

[29] S. Suryanarayanan and E. Kyriakides, "An online portal for collaborative learning and teaching for power engineering education," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 73–80, Feb. 2004.

[30] R. Atkinson, "Computerized instruction and the learning process," *Amer. Psychologist*, vol. 23, no. 4, pp. 225–239, Apr. 1968.

[31] P. Suppes and M. Morningstar, "Computer-assisted instruction," *Science*, vol. 166, no. 4, pp. 343–350, Oct. 1969.

[32] N. Alguacil, A. L. Motto, and A. J. Conejo, "Transmission expansion planning: A mixed-integer LP approach," *IEEE Trans. Power Syst.*, vol. 18, no. 3, pp. 1070–1077, Aug. 2003.

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